Radio emission processes - Part II

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1 Plasma emission

Plasma emission process is the most important coherent process to produce radio emission from solar metre - wave bursts. The important feature of coherent emission process is that the brightness temperature of the emitted radition is much higher ($T_B >> 10^{10}$ K) than can be explained by incoherent emission. The decametric radio emission from Jupiter and Auroral Kilometric emission (AKR) from the earth are also due to the coherent plasma emission process.

In a plasma wide range of wave oscillations and modes can exist. Plasma emission is an indirect emission process when a beam of electrons propagate from the flare site outwards towards the corona. As the beam of electrons propagate, they excite plasma oscillations in different layers of the Sun with increasing height. The generation of plasma waves by this process is called Langumir turbulence. The plasma waves being longitudinal electrostatic waves can not directly produce electromagnetic radiation and through some secondary process, the electromagnetic waves are generated. The basic process is that the free energy available in the Langumir turbulence is converted into electromagnetic radiation by scattering of the plasma waves on the ions or coalesclence of two waves. Radiation can occur at the fundamental and harmonic. The fundamental frequency is related to the local plasma frequency of the medium and is given by

$$\nu_p = \frac{e}{2\pi}\sqrt{\frac{N_e}{\epsilon_0 m}} \quad (1)$$

where N is the electron density and m is the mass of the electron and ϵ_o is the permittivity. The numerical value for the plasma frequency is given by $\nu_p = 9000\sqrt{(N_e)}$ Hz, where N_e is in cm^{-3}. The first step in the production of plasma emission is the generation of Langumir waves. Due to the wave - particle interaction, the wave can grow getting energy from the particle if the velocity of the particle is greater than the phase velocity of the plasma wave. For particle with velocity greater than the phase velocity of the wave, the effect is the generation of Langumir turbulence, and the reduction in the velocity of the particle. This instablity is called bump - in -tail instability. Such electrons have a veleocity distribution with a positive slope ($\frac{df(v_z)}{dv_z} > 0$) near v_ϕ as shown in the figure 1. The mutual interaction of the waves and

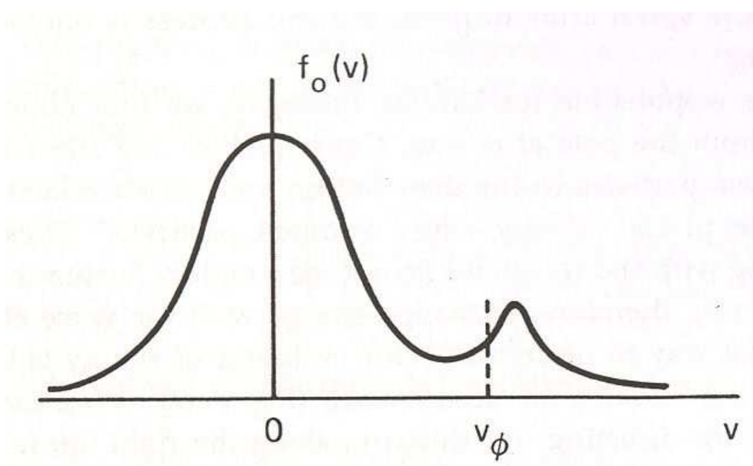

Fig. 1. Beam instability

the particles is described by a pair of quasilinear equations. The feed back on the distribution of particles referred to as quasi-linear relaxation involves smoothing out of the bump near v_ϕ to form a plateau $\frac{df(v_z)}{dv_z} \approx 0$. It was pointed by by Sturrock (1964) that in a homogeneous beam - plasma model, the beams should propagate only a few hundred kilometers before losing all their energy to the Langumir waves. But it is well known from observations that electron beams propgate through the corona and some beams are known to propagate beyond the orbit of Earth still generating Langumir waves and radiation. A number of theories have been suggested to over come this problem and stabilize the beam. One is based on the saturation of the instability due to inhomogenities in the beam. Another way is the influence of the ambient density fluctuations on the growth rate of the beam - plasma instability.

Plasma emission is a multistage process and involve (i). formation of unstable beam distribution by velocity distribution, (ii). Generation of Langumir turbulence and (iii). Conversion of plasma waves into Electromagnetic radiation. The dispersion relation between ω the angular frequency and k the wave vector for Langumir waves is given by

$$\omega^2(k) = \omega_p^2 + \frac{3}{2} v_{th}^2 \tag{2}$$

where the v_{th} is the thermal velocity and ω_p is 2π times the plasma frequency. For the above equation, the solution for ω is of the form $\omega = \omega_r \pm i\omega_i$. The variation of the amplitude with time is of the form $e^{-i\omega t} = e^{-i\omega_r t} e^{\Gamma t}$ where $\Gamma = \omega_i$. $\Gamma > 0$ means exponential growth of the perturbation. Electrons with velocity v_{th} can undergo wave -particle interaction with waves $\omega(k)$ when they fulfill the Doppler resonance condition.

$$\omega - \frac{s\Omega}{\gamma} - k_{\|} v_{\|} = 0 \tag{3}$$

Wave growth $\Gamma(k, f(v))$ or absorption rate $\Gamma < 0$ can be calculated for a given particle velocity distribution function f(v). For nonrelativistic electrons the growth rate is

$$\Gamma(k) = \left(\frac{\pi}{2}\right) \frac{\omega_p^2}{k^2} \left(\frac{\omega}{n_o}\right) \left(\frac{df_o\left(v_{\|}\right)}{dv_{\|}}\right)_{\frac{\omega}{k}} \approx \left(\frac{\pi}{2}\right) \frac{n_b}{n_o} \left(\frac{v_{ph}}{\triangle v}\right)^2 w \tag{4}$$

where n_o is the ambient electron density, n_b is the beam electron density, and $v_{ph} = \frac{\omega}{k}$ is the phase speed. For every wave - wave interaction, the energy and momentum equations have to be fulfilled. ie: matching conditions of frequencies and wave vectors.

$$\omega_1 + \omega_2 = \omega_3; \qquad k_1 + k_2 = k_3 \tag{5}$$

For example, a primary Langumir wave $(\omega_1, \mathbf{k_1})$ can couple with an ion acoustic wave $(\omega_2, \mathbf{k_2})$ to generate a secondary Langumir wave $(\omega_3, \mathbf{k_3})$. Since the phase speed of the ion acoustic wave is much smaller than for Langumir waves, the primary and secondary Langumir waves have similar frequencies and wave vectors. For conversion of plasma waves to electromagnetic waves Melrose (1987) suggested the following wave - wave interactions.

$$\begin{gathered} L + S \rightarrow L' \\ L + S \rightarrow T \\ L + S \rightarrow L' \end{gathered}$$

$$T + S \rightarrow L$$
$$T + S \rightarrow T$$
$$L + L' \rightarrow T$$

Here L denotes the Langumir wave, S the ion acoustic wave and T the electromagnetic wave. In the above equations, the first process is important to generate Langumir turbulence, while the second and third processes generate fundamental plasma emission, the fourth for scattering of the transverse waves and the last for the generation of second harmonic radiation. Growth of the Langumir waves occur until it is limited or saturated owing to (i) The beam of electrons may pass or otherwise changes its characteristics to destroy the resonance. (ii) The growing wave may be scattered or altered due to scattering off ions, or inhomogenities or low frequency waves. The wave will react on the streaming electrons diffusing them in velocity space and aslo as to remove the positive slope. Figure 2 shows the schematic diagram of the processes involved.

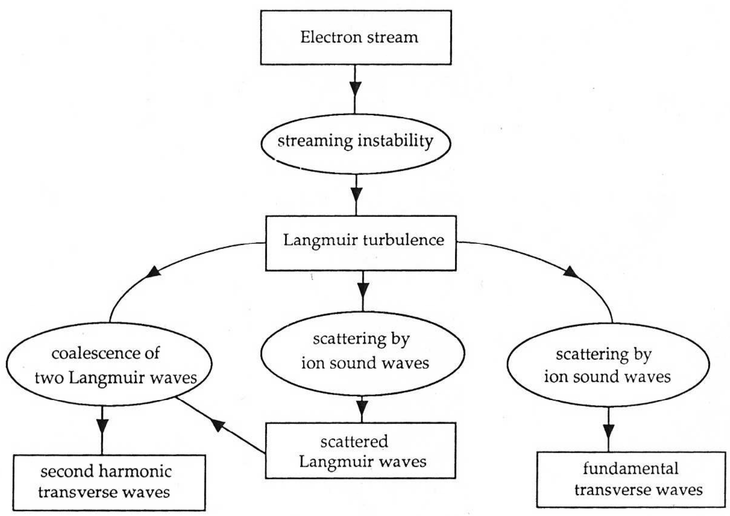

Fig. 2. Theoretical description of emission of electromagnetic radiation by an electron stream in a plasma

The saturated energy density in the Langumir waves (W_L) or equivalent the effective temperature (T_L) of the Langumir waves is defined by

$$W_L = \int \frac{k_B T_L}{(2\pi)^3} d^3\mathbf{k}. \tag{6}$$

where k_B is the Boltzmann's constant. Several studies have shown that the saturated value of W_L is $\approx 10^{-5}$ times the energy density of the background plasma ie : $\approx 10^{-5} n k_B T$. Hence the limiting value of T_L is of the order of

$$T_L \approx 10^8 \frac{v_b^2}{c^2} \frac{v_b}{\omega_p} T \tag{7}$$

which is $\leq 10^{15} K$.

Solar radio emission at a given frequency ν arise only from a region where the plasma frequency ν_p is equal or lower than ν. Because n_e decreases as a function of height in the solar atmosphere, ν_p also decreases with height, and lower frequencies must arise from greater heights. Electron densities in the range of $n_e = 10^8$ - 10^{10} cm^{-3} give rise to plasma radiation in the frequency range of 100 - 1000 MHz. During a solar flare, many types of radio bursts are generated at frequencies near the plasma frequency or its harmonics and they come from a thin layer above the plasma level. ie., above the height where $\nu_p = \nu$. In a dynamic spectrum where the intensity is displayed as a function of both frequency and time, the signature of the moving beam of particles will be displayed as a slope in the frequency - time plane. If we know the density of the medium at different heights, we can estimate the speed of the moving beam of particles. Figure 3 shows a schematic diagram of an idealized dynamic spectrum frequently produced by large flares. The nomenclature and details of different radio bursts are given in McLean & Labrum (1985).

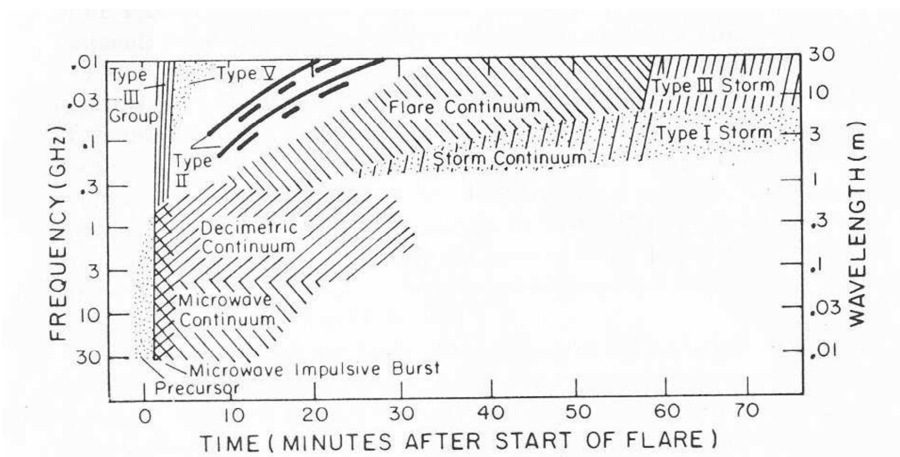

Fig. 3. Idealized solar radio dynamic spectrum after a large flare

2 Electron Cyclotron Maser Emission (ECME)

Magnetospheres of magnetized planets emit nonthermal radiation with an intensity and variability which cannot be explained as simple cyclotron emission by energetic trapped particles. Electron Cyclotron Maser Emission (ECME) has become accepted as a mechanism to explain the radio emission from magnetized planetss since 1980. MASER is the acrononym for Microwave Amplification by Stimulated Emission of Radiation. The basic requirements for MASER to operates are (i) Population inversion in the electron distribution as compared with equilibrium. (ii) A pump for the MASER and (iii) relatively strong magnetic field or low density so that the electron cyclotron frequency ω_{ce} is much greater than the plasma frequency ω_{pe}. The most common form of population inversion in the astrophysical situation is the loss cone distribution produced when electrons are energized in magnetic flux tubes that have converging legs and their foot points are in a high density atmosphere. This condition is satisfied above the auroral zone of the Earth, in the magnetosphere of Jupiter and Saturn and some magnetic flux tubes in the lower solar corona. The radio emission from these objects and the spike bursts from the Sun are usullay interpreted in terms of ECME. The brightness temperature of these emission is $\geq 10^{15}$ K and the emissions are 100 percentage circularly polarized except the Auroral Kilometric emission. In a magnetic field during an acceleration of electrons, the radiated emission is divided into both parallel and perpendicular components. The velocity distribution of the particle can be parallel to the magnetic field ($\frac{df}{dv_{\|}} > 0$) as in the case of beam of particles or perpendicular as in the case of Loss cone ($\frac{df}{dv_{\perp}} > 0$). The following discussions are based on the work of Dulk (1985).
In the case of the cyclotron MASER emission, the wave - particle resonance condition is given by

$$\omega - k_{\|} v_{\|} = s\omega_e \left(1 - \frac{v^2\|}{c^2} - \frac{v_{\perp}^2}{c^2}\right)^{-1/2} \tag{8}$$

From the above equation, we can find that for generation of radiation at frequencies near s ω_{ce}, the term $k_{\|} v_{\|}$ should be small. This happens when the radiation is produced with wave vectors almost perpendicular to the magnetic field. This occurs when the particles are trapped in regions bounded by two sites of high magnetic field like in a loss cone. From the conservation of energy and magnetic moment it can be shown that as a particle moves towards region of high magnetic field, the velocity parallel to the magnetic field direction decreases and velocity perpendicular to the magnetic field increases. Instability can develop due to this anisotropic velocity distribution and transfer energy into directly electromagnetic radiation through ECME. Due to magnetic reconnection in the solar atmosphere, acceleration of electrons takes place and the electron energy can be divided into both parallel and perpendicular to the magnetic field. Equation 8 implies that resonance is possible only if $\omega^2 < s^2\omega_{ce}^2 + c^2k_{\|}^2$. Depending on the distribution f $(v_{\|}, v_{\perp})$ of electrons in velocity space, the wave either extracts energy from the resonant electrons and grows or loses energy to them and is damped. In the former case, the intensity of the wave at any point increases exponentially with time until the MASER saturates. The dominant contribution to the growth rate Γ_s for the s th harmonic is given by

$$\Gamma_s \sim \int d^3\mathbf{v}\mathbf{A_s}(\mathbf{v}, \mathbf{k}\frac{\mathbf{df}}{\mathbf{dv_\perp}}\delta(\omega - \mathbf{k}_\| \mathbf{v}_\| - \mathbf{s}\omega_{\mathbf{ce}}/\gamma) \tag{9}$$

where $A_s > 0$. Because of the delta function this corresponds to an integration around the resonance ellipse, growth can occur only if $\frac{df}{dv_\perp} > 0$. This condition is analogus to the requirement of population inversion for the operation of a LASER. The source of free energy for all the MASER emission is believed to be a single - sided loss cone distribution. This type of distribution is formed when electrons are accelerated downwards along converging magnetic field lines near the surface of a planet or star.

Melrose and Dulk (1982) estimated the brightness temperature of Maser to be

$$\frac{k_B T_B}{mc^2} = \eta \frac{c}{r_0 \omega} \frac{\Gamma}{\omega_e} \tag{10}$$

where r_0 is the classical radius of the electron and η is the fraction of the energy density of the driving electrons converted to MASER radiation. The maximum growth rate for the fundamental x -mode for energetic electron number densities of $\sim 10^{13}m^{-}3$ and energy of 10 Kev at near 1 GHz are typically $\sim 10^{-3}$. For values of $\eta \sim 10^{-3}$, the brightness temperature $\sim 10^{17}$ K.

3 Summary

In this chapter we have discussed the coherent radio emission processes. ie. Plasma and Electron cyclotron emission mechanisms. In the case of plasma emission, the beam of particles have a non - Maxwellian velocity distribution with a positive slope in the velocity distribution. Losscones which have positive slope in the perpendicular direction to the magnetic field also produce radio emission coherently. The solar radio bursts (Type I, II, II, IV and V) below 300 MHz are usually explained by the plasma emission processes. Coherent plasma emission is also responsible for decimetric radio emission in the band 300 - 3000 MHz. The radio bursts provide useful diagonostics of density and magnetic field, complementary to other wavelengths. The Electron

Cyclotron Maser Emission (ECME) is responsible for the radio emission from magnetospheres of magnetized planets like Jupiter. The high brightness temperature ($> 10^{15}$ K) of millisecond spike burst observed during solar flares is explained by Electron cyclotron emission mechanism. The various emission processes discussed in this and the last chapter and their occurence in the solar atmopshere as a function of frequency is given in the figure 4.

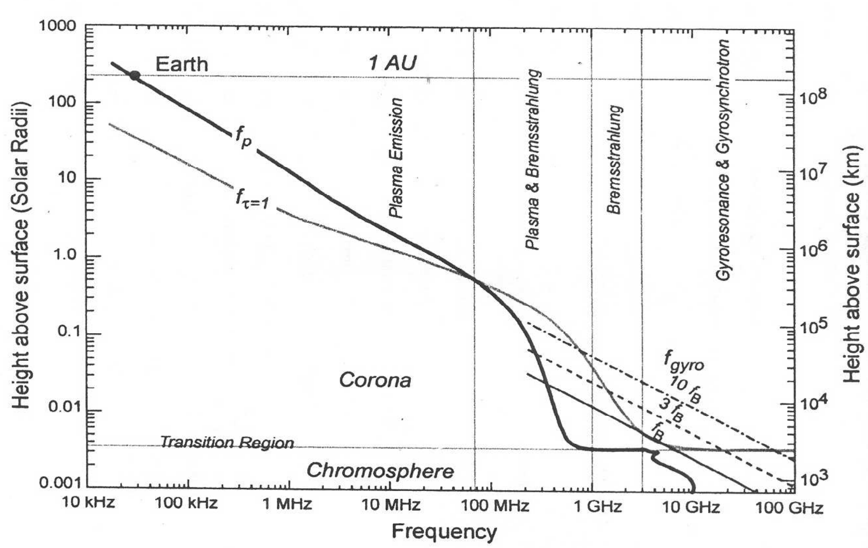

Fig. 4. Regimes of dominant emission in the solar atmopshere as a funtion of radio frequency are given(Gary & Hurford, 1989)

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